Abstract

In canonical boundary layer transition, a uniform laminar flow perturbed by 2-d T-S waves develops downstream into 3-d waves, which eventually break down with turbulent spots appearing. Previous experimental studies have established that this kind of development is absent, is by-passed, in transition induced by free-stream turbulence or surface roughness. However a common, characteristic feature of the late, three-dimensional stage is the prevalence of streamwise vorticity and streaks. Isolated and multiple streamwise vortices are present in both, canonical transition and bypass transition. This thesis describes an experimental study of the late stages of boundary layer transition after a single or a pair of streamwise vortices have formed. The present work can be considered both as a study of transition induced by surface roughness and as a study of the late stages of transition in general.

The experiments were made on a zero-pressure-gradient boundary layer in a low speed wind tunnel. Various hill configurations, mounted on a flat plate, were used to create isolated and multiple streamwise vortices. Particle image velocimetry (PIV) and hot-wire anemometry used for measurements. Numerical simulations of the initial laminar stage were carried out to understand the vortex formation at the edge of the hills. Computations have shown that the streamwise vorticity induced by the spanwise asymmetry of the hill rolls up into a single streamwise vortex. The streamwise vortex causes high speed fluid to be brought close to the wall and low speed fluid to move away. In turn, streamwise velocity profiles acquire inflections in both the spanwise and wall-normal directions. Previous studies have concluded that the inviscid instability of inflectional profiles are essential, or at least common, precursors to transition. Another view of the structure of bypass transition induced involves a secondary instability of streaks that can be sinuous or varicose. These two types follow from instabilities of the inflectional spanwise and wall-normal profiles of the streamwise velocity, respectively. However the present study confirms that the occurrence of inflections is not sufficient for transition.

The first series of experiments were with smooth Gaussian shaped hills that spanned one-half of the tunnel. Two hill shapes were taken, steep and shallow. Isolated streamwise vortices formed by the side of the hill. Hill heights were less than that of the incoming boundary layer, and they were mounted within the subcritical part of the boundary layer. At low freestream speeds, streaks formed, with inflectional wall-normal and spanwise velocity profiles, but without effecting transition. The necessary conditions for inviscid instability Rayleigh's inflexion-point theorem and Fjortoft's theorem are satisfied for these low-speed non-transitional cases. Transition observed at higher speeds show two kinds of development. With the steep hill, the streamwise vortex is not too close to the plate and it exhibits oscillations over some distance before flow breaks down to turbulence; streamwise velocity signals exhibited the passage of a wave packet which intensified before break-down to turbulence. This dominant mode persists far downstream from the hill even while the flow breaks down and frequency content grows over a range of scales. With the shallow hill, the breakdown develops continuously without such a precursor stage; there was a broad range of frequencies present immediately downstream of the hill. For the steep hill the maximum fluctuation is observed on the upwash side of the vortex. With the shallow hill, the fluctuation level is maximum at the location between low and high speed streak.

Features of breakdown to transition caused by these single streamwise vortices are found to be similar to those in transition by other causes such as surface roughness, freestream turbulence etc. With the steep hill, the growth of fluctuations (u_{rms}, the peak levels of streamwise velocity component fluctuations) is remarkably similar to that in the K-type transition. Unlike in freestream induced transition, the initial growth of $u^2_{rms,max}$ with downstream distance was not linear. Profiles of $u_{rms}/u_{rms,max}$ vs. y/δ^* where δ^*,is the displacement thickness is partially matching with the optimal disturbances, for the steep hill case. The phase velocity matches as in previous measurements of roughness induced transition. The flow exhibits the breakup of a shear layer near the outer edge of the boundary layer into successive vortices. This breakdown pattern resembles to those in the recent numerical simulations. The passing frequency of these vortices scales with freestream velocity, similar to that in single-roughness induced transition. Quadrant analysis of streamwise and wall-normal velocity fluctuations show large ejection events in the outer layer.

The difference in the route to transition between the steep and shallow hills was considered to the relative proximity of the initial streamwise vortex to the flat plate and its interaction with the wall. To examine this conjecture, two configurations were prepared to produce two types of counter-rotating streamwise vortices. One is a hill that span the tunnel except for a short gap, and the other, its complement, is a short span hill. The short-gap hill produce a pair of vortices with the common flow directed away from the wall. This resulted in a separation bubble that formed a short distance downstream and breakdown to turbulence. The short-span hill configuration seems to have a stabilizing effect. With the short gap hill, transition occurs for lower freestream speeds than with the isolated vortices considered before. Also, the breakdown location is further downstream when the gap is larger. The initial velocity profiles look similar for transitional and non-transitional flow cases, and are inflectional, which clearly indicates that inflectional instabilities are not effective here. A separation index was computed to identify unsteadiness of the separated flow region. The separation is itself steady, whereas the reattachment is unsteady. Fluctuations grow near this reattachment zone. The unsteadiness of the reattachment coexists with the appearance of strong fluctuations and transition. It is likely that the this last stage of breakdown results when the shear layer, lifted up by the separation bubble, breaks down near the edge of the boundary layer and the consequent unsteadiness is in the reattachment also. Coherent cat's-eye-like patterns were observed in a longitudinal, plane normal to the wall. With isolated vortices sinuous oscillations and with streamwise vortex pairs varicose oscillations were observed in wall-parallel planes. In both cases passing frequency of these vortices scales with freestream velocity. Λ-type vortices were identified in spanwise plane with counter-rotating legs.

These experiments have identified some possible roles of streamwise vortices in the last stages of boundary layer transition. Vortices may undergo their own instability in the background shear layer, evident as oscillations, if they are not too close to the wall. Otherwise the breakdown is without such a stage. Wall interaction of these vortices seems to be a necessary last stage. Inflectional instability is not indicated. Wall interaction that results in separation results in breakdown in the unsteady reattachment zone. Breakdown coexists with the reattachment and not at separation, even though it may be the separating shear layer that breaks down.